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STUDY TO DETERMINE OPTIMUM EXTERIOR LIGHTING FOR AIRCRAFT

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Maurice K. Laufer

Grimes Manufacturing Company

October 1955

Equipment Laboratory
Contract No. AF 33(616)-2141
Project No. 6062
Task No. 60461

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by Mr. Maurice K. Laufer of the Grimes Manufacturing Company of Urbana, Ohio, under Contract No. AF 33(616)-2141, Project No. 6062, and Task No. 60461. Mr. Ronald K. Davis of the Equipment Laboratory was project engineer for the basic research and development work.

ABSTRACT

Aircraft exterior lights serve two main functions: (1) to be seen by and (2) to see by. The latter pertains to such units as landing, taxi and wing inspection lights. The other function has been the major subject of this report and is concerned primarily with making the presence and flight direction of an aircraft known to other pilots and control tower operators for prevention of collisions. An analysis of the range requirements of position lights is presented and its application to the candle power performance is discussed and compared with current specifications. Flight test results on inboard mounted forward position lights are examined. Flashing frequencies and on-to-off ratios were extensively studied in flight for standard exterior lighting and when anti-collision lights are used. The advantages and limitations of anti-collision and condenser discharge "conspicuity" lights are discussed. Some inherent limitations of the optical performance of "flush" transparent covers or enclosures of exterior light fixtures are presented.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or the conclusions and recommendations contained herein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:

for S. T. SMITH
Colonel, USAF
Chief, Equipment Laboratory

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I. INTRODUCTION

Position or navigation lights are normally thought of when the phrase, aircraft exterior lights, is seen or heard. For conventional aircraft before the introduction of swept back and delta wings, position lights consisted of wing tip and taillights. For some small private type aircraft the wing tip lights and taillights comprise the entire exterior lighting system. Their function is to make known to pilots of other aircraft and control tower operators at night the position and an indication of the direction of motion of the aircraft on which they are mounted.

This study to determine optimum aircraft exterior lighting has concerned itself primarily with the problem: The determination of the optimum nighttime position and direction of motion information that can be presented by means of lights consistent with (1) practical power consumption, (2) aerodynamic configuration, and (3) the existing visual training and experience of all aircraft pilots. These considerations have included modern high speed aircraft having wings too thin to accept conventional light sources.

II. HISTORICAL

Today several varied, though similar, position light systems are employed on aircraft in the United States. A brief history of the evolvement of these systems is not only of interest but will help justify some of the conclusions made later in this report.

The earliest prescribed position light configuration was patterned upon that used for navigation lights by boats on water. One or more red lights were to be shown from the left wing tip so that at least one light was visible everywhere within the vertical dihedral angle from directly forward and outboard through a horizontal angle of 110°. Green light from the right wing tip filled in a similar vertical 110° dihedral angle from forward around to the right. White light from the tail took care of the remaining directions, namely, the 140° vertical dihedral angle centered about directly aft. In due time colormetric data for the colors and photometric data as to minimum intensities in various directions within prescribed dihedral angles and maximum intensities in overlapping regions were forthcoming.

These steady burning red, green and white position lights prevailed until about 1940. Then several commercial air lines requested that the Civil Aeronautics Administration improve the conspicuity to the rear because of several near air-to-air collisions and one actual collision of a taxiing aircraft running into the rear of another parked temporarily in its path. One near ~~air-to-air~~ collision concerned a bomber formation overtaking from a rearward angle and subsequently passing in front of an aircarrier. There were also reported several occurences where an aircraft of faster approach speed almost overtook an aircraft directly ahead during landing because the taillight ahead was mistaken for a white light on the ground. Susbequent tests conducted by the National Bureau of Standards, which included observations by many pilots, air line personnel and CAA personnel, led to the adoption of the alternately flashing white and red taillights.

The flashing of the taillights increased the conspicuity sufficiently so that soon the wing tip lights were being flashed in unison with the white taillight. Not too long thereafter white fuselage lights flashing with the red taillight were added to comprise the total aircarrier position light system. Military aircraft have partially gone along with this flashing configuration. The taillight consists of alternately flashing white and yellow lights with the wing tip lights flashing with the white taillight. In some cases white fuselage lights burn steady and in others flash with the yellow taillight.

Flashing of position lights on small private type aircraft is not mandatory. If a flasher is used with only the red and green wing tip and white taillights, these three lights are flashed in unison.

One further variance should be noted. The wing tip lights on some types of military aircraft that may be flown in close formation at night serve a dual purpose. Specifications require that each wing light be visible within a hemisphere bounded by a vertical plane containing the flight axis. In this manner each light also serves as a wing formation light. Also, for these cases the light output of the two wing tip lights together completely overlap the taillight region. However, the prescribed minimum intensity in these overlapping regions is relatively very low.

Despite the variations noted, all pilots, military and civilian including private flyers, were trained to look for and have always observed at night red left and green right wing tip lights and at least a white taillight on every standard aircraft being flown at night. Moreover, the basic regions prescribed for each of these colors always have been from dead ahead and outboard 110° for each of the winglights and the remainder of 360°, namely 140° aft for the taillight for at least private and commercial aircraft. Taillights on military aircraft cover the entire rear hemisphere.

III. BASIC REQUIREMENT AND INHERENT LIMITATIONS OF POSITION LIGHTS

The first and foremost requirement for any position light system is that it shall have maximum conspicuity. By conspicuity is meant attention getting or attraction producing effect generated in the eyes of any pilot or control tower operator located anywhere from which the system can be seen. Far better be it that a system makes known the presence of the aircraft on which it is installed at an appreciable distance rather than to provide lots of other information too late. Additional information regarding direction and speed are desirable but are nevertheless of secondary importance. Thus the essential purpose of a position light system is that it reveal the existence of the aircraft at night at the earliest possible moment.

But earliest possible moment implies a rather extended visual range of the system. Unfortunately atmospheric conditions are too often such that no practical light source has a visual range sufficient to be useful for avoiding collisions between aircraft. During overcast conditions, even the sun's position is wholely indeterminant from below the cloud layer. Coupled with adverse weather conditions is the ever increasing speed of modern aircraft. What used to be an early enough moment or adequate visual range during moderately good atmospheric conditions is now insufficient by far because of the high rate of closures of some of todays faster aircraft.

Hence the position light problem like so many others has a basic requirement which much of the time seemingly can never be met. The best compromise therefore is the one which will provide the maximum protection against collisions for any given penalty on the performance and economical operation of the aircraft. The remainder of this report is concerned in general with an evaluation of these several factors and the conclusions that may then be made.

IV. RANGE REQUIRED OF POSITION LIGHTS

The distance at which it is necessary to see the position lights on one aircraft from another in order to be able to take preventive action for averting a possible collision depends on two major factors. One is the relative velocity of the two aircraft which includes their relative directions of flight. The other is the time required for the pilots to detect the presence of each other plus that required to initiate and complete whatever action may be required. The term "warning time" has been used for this total period. It includes successively detection, evaluation, decision and execution time on the part of the pilots and response time by the aircraft. The determination of warning time is a rather extensive subject but sufficient for this study is the knowledge that an appreciable portion of a minute is involved. In some exceptional cases a full minute or more may be required.

Figure 1 shows the geometry of the range determination problem wherein two aircraft are flying a collision course. The symbols used have the following representation:

C -- Point of impending collision.
A -- Position of aircraft flying at speed S towards C.
B -- Position of aircraft flying at speed fS towards C.
f -- Some fractional value between 0 and 1.
b -- Angle between direction of flight of slower aircraft at B and direction from B to A.
t -- Warning time
R -- Required position light range

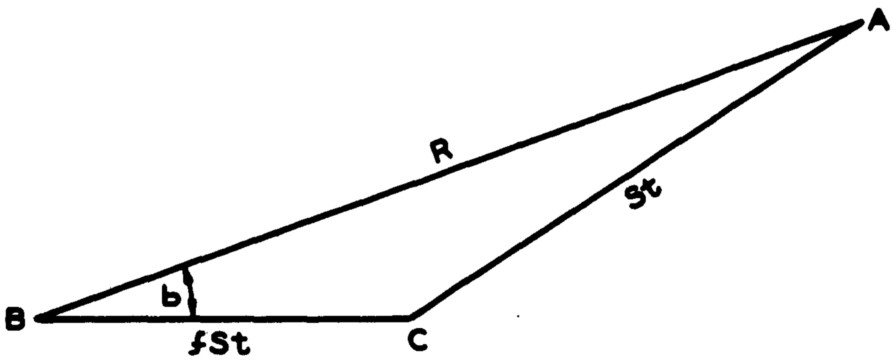

FIGURE I. GEOMETRY OF POSITION LIGHT RANGE DETERMINATION

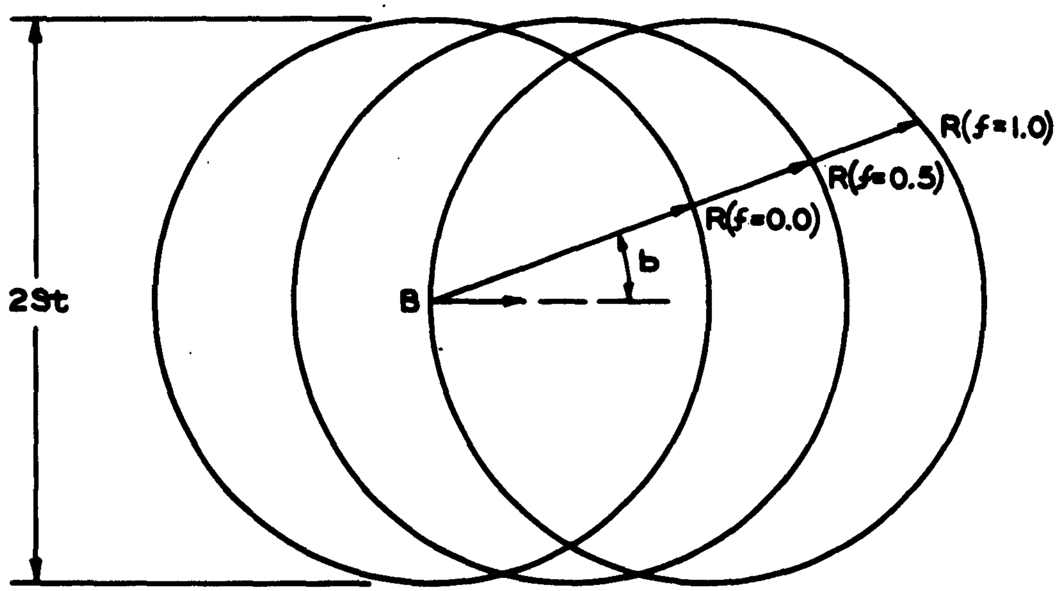

FIGURE 2. RANGE R OF POSITION LIGHTS AS A FUNCTION OF b FOR f=0.0, 0.5 AND 1.0 WHERE $R^2-2RfSt+(fSt)^2=(St)^2$

By the cosine law for obtuse triangles,

$$R^2 - 2RfSt \cos b + (fSt)^2 = (St)^2 \qquad (1)$$

This equation expresses R as a function of f, S, t and angle b. If f, S and t are held constant one has an equation in polar coordinates (R,b). As such, it is the equation of a circle with center at (fSt, 0) and radius St. With reference to Fig. 1 the origin of coordinates is at B and R is the required range of the position lights on the slower aircraft as a function of b for the constant values of f, S and t.

As f varies from 0 to 1 there results a family of circles of radius St but with different centers positioned respectively from the origin of coordinates B to (St,0). Three circles of the family, f equal to 0.0, 0.5 and 1.0, are shown in Fig. 2. For f zero, as would be the case of a hovering helicopter, the required position light range is St in every direction as depicted by the left hand circle with center at B.

At the other extreme for f unity as when both aircraft have equal speed S the required range can be expressed in the simplified form 2St cos b. For this one case where the right hand circle is relevant, the required position light range applies equally well to the aircraft at A of Fig. 1 as well as to the one at B. This follows because the obtuse triangle of Fig. 1 reduces to an isosceles triangle with equal sides St and equal angles b. It may be noted that for this case the required range at 45° to the flight axis is more than 70% of that required dead ahead. To the rear however, the required range is zero. This is as would be expected when one realizes that there can be no collision if the aircraft to the rear cannot exceed the speed of the one ahead.

If the speed S represented the top performance of any aircraft, then the range 2St cos b would be adequate from dead ahead to 45° outboard. But this same fastest aircraft must slow down for landings and at times will have zero speed when initiating take-offs or making sharp turns while taxiing. Consequently the envelope of the family of circles of Fig. 2 could very well represent a desirable range vs. direction of position lights on the fastest aircraft when performance at other than maximum speed is also considered.

It should be noted that Figs. 1 and 2 are not restricted to a horizontal plane. They are completely general and apply if one or both aircraft are ascending or descending no matter how steeply. Consequently the position light requirements as depicted by Fig. 2 cover upward and downward directions as well as forward, aft and outboard.

V. CANDLE POWER VS. RANGE OF POSITION LIGHTS

The intensity in candles required of an essentially point source signal light in order that it may be seen at a given range was first formulated by Allard. (1) It is determined by the equation

$$I = E_0 R^2 / T^R \quad (2)$$

Here E_0 is the threshold illumination, R the given range and T is the atmospheric transmission per unit distance. The equation is simply a composite expression of the eye's illumination threshold sensitivity to point type light sources, the inverse square law of illumination and the atmospheric attenuation of light.

"Threshold" seeing is a dubious condition. Whether one means just or just not visible is debatable. Consequently for signal light practice a value of 0.5 mile candle, roughly 100 times threshold, has frequently been used to insure "certain" rather than "dubious" seeing. Obviously the value used will affect the detection phase duration of the total warning time period. A precise value is not of prime importance for this study because the factor T^R so greatly affects the required candle power for all but very short ranges when other than very clear atmospheric conditions exist. This will become evident as the following explanation and accompanying data in Table I and the resulting computed candle power values are presented.

In the discussion on the required range of position lights, reference was made to the envelope of the family of circles as affording a desirable range distribution. This distribution has 2St dead ahead for the maximum and St towards the rear for the minimum range. In Table 1, speeds and warning time periods have been chosen such that if one product is used as 2St, a preceding one will serve as St or vice versa. The initial speed of 120 mph was chosen because it is a multiple of 60 mph and it represents about the average landing speed of modern aircraft. The succeeding values, i.e., 240, 480 and 960 mph are respectively more or less representative of (1) slowed-up speeds for operating in the vicinity of airports or in congested traffic areas, (2) maximum cruising speed of propellor driven aircraft and (3) maximum speed of jet aircraft now in production. Two values of warning time period, 25 and 50 seconds, have been used. It is believed that an adequate warning time period would be bounded by these two values for most all situations encountered with fixed wing aircraft now in operational use or currently being procured for such usuage.

Two values for the atmospheric transmissivity have been used in Table I. The value 0.90 per mile corresponds to very clear weather. The second value 0.22 per mile corresponds to the minimum transmissivity at night for which the CAA will permit operations under visual flight rules. This VFR minimum at night corresponds to a visual range of 3 miles for a 25 candle lamp at night, the luminous object preferred by the U.S. Weather Bureau for nighttime visual range estimates. The last six columns of Table I list computed values as indicated.

TABLE I

INTENSITY REQUIRED OF AIRCRAFT POSITION LIGHTS

AS COMPUTED FROM $I = E_o R^2/T^R$

FOR E_o = 0.5 MILE CANDLE

AND T EXPRESSED IN TRANSMISSIVITY PER MILE

S	t	R = 2St	R^2	$1/T^R$		I Candles	
				T = 0.90	T = 0.22	T = 0.90	T = 0.22
(mph)	(seconds)	(miles)					
120	25	1.7	2.8	1.2	1.2×10^{1}	1.7	1.7×10^{1}
120	50	3.3	11.1	1.4	1.6×10^{2}	7.8	8.7×10^{2}
240	25	3.3	11.1	1.4	1.6×10^{2}	7.8	8.7×10^{2}
240	50	6.7	44.	2.0	2.4×10^{4}	44.	5.4×10^{5}
480	25	6.7	44.	2.0	2.4×10^{4}	44.	5.4×10^{5}
480	50	13.3	178.	4.1	5.9×10^{8}	360.	5.2×10^{10}
960	25	13.3	178.	4.1	5.9×10^{8}	360.	5.2×10^{10}
960	50	27.	710.	16.6	3.4×10^{17}	5900.	1.2×10^{20}

A comparison of the fourth and fifth columns of Table I shows that the fourth column values are the largest. Conversely, on comparing the fourth and sixth columns, the values in the sixth column not only start larger out increase at a very much more rapid rate. Thus it has become evident as previously intimated that the term $1/T^R$ predominates when other than very clear atmospheric conditions exist. This is further evidenced upon comparing the seventh and eighth columns. In the seventh, none of the candle power values are exceedingly large. But the last two values in the eighth column exceed the luminous intensity of any continuous light source that man has created to date. Thus the candle power requirements of position lights for **high performance aircraft** are unattainable **when the visual range is three miles.** It only compounds the absurdity to consider really bad weather conditions such as dense fog or clouds where the atmospheric transmissivity is less than 10^{-40} per mile.

It is noteworthy that for a range of 6.7 miles, the corresponding required intensity of 0.54 million candles is about that of the larger landing light units in service. This shows that it would be possible to provide a signal that can be seen 6.7 miles at night under atmospheric conditions when the aircraft could not be seen further than approximately 3 miles during the daytime.

VI. LUMINOUS FLUX AND POWER REQUIREMENTS

By definition, candle power in any direction is the luminous flux per unit solid angle emitted by the source in that direction. When the desired intensity distribution pertains to a large solid angle, the total luminous flux and consequent power required may be appreciable. If the candle power distribution has axial symmetry, the integral for obtaining total luminous flux is (2):

$$F(b)=2\pi\int_{b_1}^{b_2} I(b)\sin b\,db \qquad (3)$$

The envelope of the circles of Fig. 2 may be described by the following equations:

$$R=\begin{cases} 2St\cos b, & 0^\circ \le b \le \pm 45^\circ \quad (4a)\\ St\csc b, & \pm 45^\circ \le b \le \pm 90^\circ \quad (4b)\\ St, & \pm 90^\circ \le b \le \pm 180^\circ \quad (4c)\end{cases}$$

Substitution of these values of R into equation 3 gives analytical expressions for I(b) everywhere about the aircraft at B in Fig. 2 as follows:

$$I(b)=\begin{cases} E_0\,(2St\cos b)^2/T^{2St\cos b}, & 0^\circ \le b \le \pm 45^\circ \quad (5a)\\ E_0\,(St\csc b)^2/T^{St\csc b}, & \pm 45^\circ \le b \le \pm 90^\circ \quad (5b)\\ E_0\,(St)^2/T^{St}, & \pm 90^\circ \le b \le \pm 180^\circ \quad (5c)\end{cases}$$

Formally, substitution of these values of $I(b)$ into equation 3, evaluation of the subsequent definite integrals, and summing the three numerical values thus obtained would result in the desired total luminous flux. In practice however, only the first and third integrals have solutions in closed-form and the solution for the first integral is somewhat complex. Consequently, a type of numerical integration known as the zonal method (3) of computing the luminous flux from candle power data is advantageous. Mathematically, the approximate lumens in any zone bounded by the angles b_1 and b_2 is given by

$$F_{1,2} = 2\pi(\cos b_2 - \cos b_1)\, I(b_{1,2}) \tag{6}$$

where $I(b_{1,2})$ is usually taken as the intensity at the mid-zone angle $(b_1 + b_2)/2$. This is the integrated expression for equation 3 if $I(b)$ were not a function of b.

In converting total flux to power required the following estimates have been made:

a. Luminous efficiency of source — 15 lumens per watt
b. Source lumens utilized — 60%
c. Reflectance and/or transmittance of optical system — 85%
d. Transmission of red or green filters — 20%

This gives an overall efficiency of 1.5 lumens per watt for red or green colored and 7.5 lumens per watt for uncolored light. These values may be high since one cannot always devise the optical system so that the luminous energy is redirected as desired. However, the assumptions made should be attainable in some cases.

For numerical computations, (4) "We used (and still use) the following relations in obtaining visibility from transmissometer data:

$$\text{For day} \quad T^R \quad 0.055 \tag{7}$$
$$\text{For night} \quad T^R \quad 0.0034R \tag{8}$$

The day relation assumes large black marks as a standard and the night relation assumes 25 candle lamps. The relations were recently checked by the Weather Bureau using their observers. No significant differences were found."

The results of some of the computations of luminous flux and power required of position lights are summarized in Table II. The first tabulated values of 2St and T are taken from Table I and correspond to the 0.54 million candle power required dead ahead. As previously mentioned, this candle power is obtainable from a 600 watt landing light. However, as shown by the last three tabulated values in row 1 of Table II, some 21 to 22 kilowatts would be required to provide for the luminous flux needed by the corresponding intensity distribution. In terms of the load on the aircraft main or auxiliary engines, 300 to 400 horsepower would have to be diverted for providing the necessary electrical energy. It should not be overlooked that these considerations refer to the intermediate value of 0.54 million candles of Table I, not the 10^{10} and 10^{20} candle power values which are impossible.

TABLE II

TOTAL FLUX AND POWER REQUIRED BY AIRCRAFT POSITION LIGHTS

2St (miles)	T (per mile)	Flux (Lumens) Forward 0-90° cone*	0-110° cone*	Total 0-180° cone*	Power (Watts) Forward 0-90° cone*	0-110° cone*	Total 0-180° cone*
6.67	0.22	30,900	31,100	31,500	20,600	20,700	20,800
5.0	0.56	309	338	393	203	223	230
3.9	0.56	112	125	149	65	83	86
3.2	0.56	56	63	76	37	42	44

* 0-90° cone is the forward hemisphere,
0-110° cone is forward hemisphere plus 20° aft, and
0-180° cone is total spherical coverage, 4π Steradians

The basis for the values in the second row is arbitrary to the extent that 5 miles was chosen for both 2St and for R in equation 7 for determining T to be 0.56 per mile. This choice presumably, at first thought, would provide equal chances of avoiding collisions during day or night. But the basis for equation 7 is large black objects which offer maximum contrast as is not the case of an airplane. Conversely, our computations include the use of 0.5 mile candle for E_o which is appreciably greater than threshold illumination for signal lights. Thus for both conditions, the practical considerations favor the nighttime situation. Consequently one or both of the tabulated values of 3.9 and 3.2 miles for 2St in Table II may represent possibly a more realistic nighttime equivalent to the actual daytime visual range of an aircraft when T = 0.56 per mile than does the 5 mile value.

These two values, 3.9 and 3.2 miles for 2St were determined to the closest 0.1 mile by assuming 80 and 40 watts respectively as being available for providing the necessary luminous flux when T = 0.56 per mile. These wattages were chosen because 40 and 20 watt lamps are currently used in wing tip light fixtures. Two lamps are required to fill the total 0-110° cone of Table II. The 20 watt lamp is the AN3122-1524. This type lamp is presently used on nearly all aircraft in operational use today. The 40 watt lamp, A-4174 is relatively new and has not been used extensively.

For 2St equal to 3.55 miles, the average of 3.9 and 3.2 miles, the warning time for 180 mph would be 35.5 seconds. The CAA is now evaluating at Washington National Airport the safety conditions resulting from placing a maximum air speed of 180 mph on all aircraft operating in the immediate vicinity of the terminal even during VFR conditions.

It is of interest to compare the minimum specified candle power values for the AN3122-1524 lamp with those found in determining 3.9 and 3.2 miles for 2St for the third and fourth rows of Table II. These comparisons are shown in Table III. The actual values listed in the third and fourth columns are five times the computed candle power in order to compensate for the 20% transmission of red and green filters since the corresponding candle power data for AN3122-1524 as given in MIL-L-6725 is for the lamp only without cover glasses.

TABLE III

HORIZONTAL CANDLE POWER DISTRIBUTION
OF WING POSITION LIGHT LAMPS

	Candle Power		
Angle Outboard (degrees)	Min.Spec. AN3122 -1524	2St = 3.2 mi and T = 0.56 (approx. 20W)	2St = 3.9 mi and T = 0.56 (approx. 40W)
0	180	164	365
10	180	154	343
20	180	129	281
30	40	96	202
40		62	126
50		37	71
60	35	25	47
90	30	16	29

The significant difference between AN3122-1524 and the theoretical candle power distributions exists in the 20 to 50 degree region. As indicated by Table III, the minimum prescribed intensities for AN3122-1524 are deficient in this region.

VII. OPTIMUM FLASHING RATE

A flashing light is much more conspicuous than a steady one. But a quick flash once a minute is of little use for aircraft position lights when warning times are of this duration or less and the detection phase is only a portion thereof. Thus if position lights are to be flashed it is obvious that the flashing must be fairly rapid but not of such a high rate that the short individual flashes loose too much of their conspicuity.

An experimental flasher was constructed which would permit two types of variation: (1) the number of flashes per minute and (2) the ratio of "on" to "off" time for each cycle. The flasher was installed in a Beech

Bonanza aircraft and used to flash in unison the wing tip and white tail position lights. The wing tip lights were initially equipped with #1512 lamps and the taillight with a #93 lamp. Later the wing tip fixtures were changed to permit the use of 40 watt #A4174-12 lamps in each and the #93 lamp in the taillight was replaced by a #1777 lamp.

Observations were made both from the ground and from another Bonanza aircraft. They included close-up and far ranges and many angles of view with the airplane passing across, approaching, receding and most other angles in between with respect to the position of the viewers. The observers included three pilots and several people experienced in the development of aircraft lighting equipment.

All observers agreed that the optimum rate of flashing was somewhere in the range of 70 to 110 flashes per minute. At 120 flashes per minute, all observers agreed that the conspicuity of each individual flash was appreciably less than at the 80 or 100 rate. At 60 flashes per minute, the observers also agreed that the overall appearance was less effective than at the somewhat faster rates. These results agree in full with those obtained at the National Bureau of Standards during the tests that preceded the formulation of the red and white taillight system which is required on air carrier aircraft.

Initial testing of the on to off ratio soon made it obvious that the optimum ratio would be the largest that could be attained subject to the maintenance of a distinct off period. Later tests showed that for the 12-volt lamps tested (Bonanza aircraft system voltage), lamps having rated currents up to 1.5 amperes gave a satisfactorily distinct off signal when they were disconnected from power for as short an interval as 0.15 second. When higher current lamps up to 3.0 amperes were used, the off time had to be increased to almost 0.20 second. Flasher specifications would thus depend on lamps employed and these minimum "off" times should be considered when specifying the maximum flashing rate.

It is noteworthy that the above testing showed that the "grasshopper" effect was reduced to almost insignificance by using off periods of about 0.2 second. The aircraft traveled such a short distance between on times and the off period was sufficiently short so that the observers seemingly were able to bridge the gaps in the discontinuous motion. When longer off times were presented, the almost continuous apparent motion broke up into a series of a disconcerting "jumps" which has been called the grasshopper effect.

Whether or not the 0.2 second off time is short enough to overcome the grasshopper effect on higher speed aircraft observed at short ranges is problematical. For long visual ranges where the rate of change of visual angle is small, 0.2 second should suffice.

VIII. SECTOR COVERAGE VS FLIGHT RULES

According to the rules of aerial navigation, an aircraft approaching from the right or being overtaken from the rear has the right of way. Moreover, the other aircraft must give way to the right and go behind or pass on the right. To this is added the one remaining situation: When two aircraft are approaching head-on, both must give way to the right. At night, the various colors presented by the position light system affords information as to the direction of flight of the aircraft on which the system is installed.

The overall spherical coverage of the existing position light system breaks up into six sectors resulting from the overlaps of the red, green and white signals. These six sectors are approximately as follows for military aircraft: (1) dead ahead and outboard each side about 8 degrees making some 16 degrees total of red and green; (2) outboard on the port side from about 8 degrees to about 82 degrees making some 76 degrees of red only; (3) a similar green only sector on the starboard side; (4) outboard on the port side from about 82 degrees to about 118 degrees making some 36 degrees of red and white; (5) a similar green and white sector on the starboard side; and (6) a white only sector to the rear about 124 degrees total spread. Thus at night, the overtaking case is straightforward. Whenever the taillight (single or two colored pair) or the taillight plus a red or green wing tip light is observed, one would, if necessary, give way so as to pass on the right. Similarly, the dead ahead situation is also definite. If both wing tip lights are observed at the same time one would give way to the right.

But when one observes only a red light over his own green or vice versa the situation may be very hazardous. Lacking any other knowledge of the motion of the other aircraft, the observation of a red position light over your own green gives the other aircraft the right of way. Moreover, you must give way to the right. Only a few moments with paper and pencil are necessary to depict situations where this blind giving way to the right would turn you into a collision course whence previously none existed. In other cases, giving way to the left may be seen to be the proper maneuver. It would seem to be almost obvious that part of this uncertainty arises from the excessive angular width of these red only and green only sectors. In other words, more precise information is required.

From the standpoint of safety only, no objection can be raised to a distinct rear sector of a full 180 degrees. Further, if from about 55 degrees outboard from dead ahead to about 80 degrees outboard, an intentional overlapping of the taillight and red or green wing tip light sectors existed, the present red and green only sectors would be decreased from about 75 degrees for military aircraft and about 95 degrees for non-military aircraft to about 45 degrees. This would improve considerably the precision of the direction of motion information in precisely the sector where it is most needed. These improvements could be made without changing the basic intent of the present color system. Thus it would not force every pilot to attempt to forget past learning and experience and substitute something new. It simply adds precision to the interpretation of observations which would not differ from those to which they are accustomed. From the lighting fixture design aspect, fewer lumens would be required for the red and green sectors since the coverage would be reduced. For the clear taillight, the additional coverage would not be difficult to attain since one is not forced to compensate for the absorption by the red and green filters.

IX. POSITION LIGHT INSTALLATION LOCATION

Wing tip installation of the red and green forward position lights has several advantages. If visible directly or by auxiliary means from the cockpit, they assist the pilot in maneuvering in crowded quarters such as at loading ramps and parking between other aircraft. As previously mentioned, wing tip position lights may serve also as formation lights. For carrier based aircraft, the extreme separation of wing tip mounting provides for maximum roll information to the landing signal officers during night landings. However, each of these advantages are incidental to the original design objectives of forward position lights and they each require relatively low light intensities. Moreover, extreme swept-back and delta wing configurations may place the wing tips too far aft for lights at these points to be as useful as in the past for these incidental functions.

But the major consideration with respect to wing tip location of forward position lights on many modern aircraft is that the wing thicknesses have been reduced to such an extent that the heretofore normal installations cannot be tolerated for aerodynamic reasons. If these modern wing tip designs are going to force a change in location, it is desirable to know what effect the change will have on the basic functional performance of the forward position lights. In order to obtain at least a partial answer to this problem, red and green wing position light fixtures were mounted just ahead of the wing roots on the side of the fuselage of an Ercoupe aircraft. This installation resulted in a separation of about 42 inches between the red and green light sources.

Air-to-air flight test observations included near and far ranges and most all course configurations between the observed and observing aircraft. During the observations, the regular wing tip installed lights were alternated with the test lights, using a 10 to 15 second period for each in order that comparisons could be made. Except when both the red and green units were visible at the same time, no noticeable difference was detected in the position light signal from the regular and test lights. The exception arises because of the limited resolving power of the observers' eyes. For the 42 inch separation, observations as close as even 0.5 mile revealed an overlapping of the red and green signals that was somewhat startling when first seen. At these short ranges, the illumination at the observers' eyes is many times higher than when the regular lights are observed at the minimum range for which the red and green lights are irresolvable. This large difference in apparent light signal strength accounts for the striking difference in the appearance of the head on view of the inboard and regular wing tip installations at their respective irresolvable ranges.

However, having once seen at close range the composite red and green marbled signal of closely spaced position lights, there would be no question as to its interpretation if seen again at some future time. Moreover, the lack of resolving power could be nullified for both regular and very close spacing by flashing these forward position lights alternately.

For single light signals such as the red or green alone, the flight tests confirmed what one would expect: Normal viewing distances of position lights are large compared to the size of the aircraft and hence installation locations are of no importance when the lights are seen singly. However composite viewing of two lights at a time creates two problems. The first is that of resolving power just mentioned and which would be permissible by learning to recognize the composite signal or side stepped by flashing the lights alternately. The alternate flashing solution however becomes somewhat involved when the entire system comprises more than two colors. Moreover since for maximum effectiveness flashing should provide for on to off ratios appreciably greater than unity, the alternate flashing solution would not seem to be too desirable even for a simple two color system.

The second problem when viewing two lights simultaneously concerns their relative locations and the interpretations one may thereby make. Previously, when viewing a conventional airplane from slightly aft of directly to the side one would see the taillight to the right of the red or to the left of the green wing lights depending upon which side is in view. But for a delta wing configuration, these relative positions of wing tip and taillights may be reversed. Such a reversal could be perplexing until it becomes familiar and pilots learn to react to seeing red and white or green and white signals irrespective of their relative locations. Installation of the red and green forward position lights on the side of the fuselage fairly well forward instead of on the wing tips would overcome this problem for extreme swept -back and delta wing aircraft.

Another aspect of simultaneous viewing of two position lights is the possibility of estimating the range by observing the apparent separation of the two lights being viewed. Such estimations from dead ahead would have to be greatly revised, if they could be made at all, for forward position lights mounted on the side of the fuselage. However, it is very doubtful that pilots give any appreciable real consideration to this possibility. Wing spread, overall length and relative bearings vary too much between different aircraft and for different situations for much credence to be given to such estimates.

Spacing of lights so closely that they cannot be resolved could be impractical in some specific cases. Irresolved forward position lights could not be used by Landing Signal Officers for roll information. Likewise, such a spacing would prohibit useful interpretations of the signal from an aircraft approach light system installed in between such lights. For the latter, it would be essential that all three lights be resolvable within the ranges required for carrier landings. This may require the extinguishing of closely spaced forward position lights and the employment of small, less intense outboard lights for night carrier landings. Lights of this type could also be used for the other incidental applications previously mentioned for wing tip fixtures. The term "clearance lights" has been used for lights which mark the extremities of motor truck bodies and similar vehicles.

X. ANTI-COLLISION LIGHTS

Because of known inadequacies of conventional position lights, considerable time and effort has been expended on the development of other types of signal lights which might be used in conjunction with or even in place of those now employed. One noteworthy development was the "sweeping" wing tip units evaluated by the CAA Technical Development and Evaluation Center, Indianapolis. Small searchlight type units are enclosed in wing tip pods with conventional colored beams, red on left and green on the right. The sealed beam type lamp units are oscillated about a vertical axis such that the high intensity beams sweep outboard from forward to some predetermined angle up to 180 degrees and back to forward each cycle. The required size of the enclosing pods is the main drawback of these units.

Somewhat similar units that provide a rotating red beam and which are mounted on top of the vertical fin or on top and/or bottom of the fuselage have had wide acceptance. The designation "anti-collision" light has been given to such units and their use is to be required on all aircraft under CAA jurisdiction with certificated weight of 12,500 pounds or more before the end of 1956.

The acceptance given to rotating beam units deserves examination in order that the merits and limitations may be understood. In general, the beams (at least the main beam) from some of these units fill a solid angle of less than 0.1 steradian. Conversely, each conventional red or green wing tip position light must fill appreciably more than a quarter of a sphere, actually more than 4.2 steradians because of the necessity of overlapping regions. Thus on the basis of solid angle coverage only, the anti-collision units should provide intensities at least 42 times the average provided by currently used wing tip fixtures. Another comparison, is the relatively large frontal area of these newer units. In terms of AN3033 wing tip fixture, the frontal areas of anti-collision lights vary from about 7 to more than 15 times bigger. The main reason for this increased size is to provide space for lamps of higher wattage. But one may very well question why such a size is suddenly tolerable with the ever increasing speed of aircraft and the consequent enhanced attention being given to aerodynamic drag and weight. Two pertinent reasons are that (1) the subject higher speeds have almost forced the use of more effective light signals and (2) increased aircraft traffic density likewise required some such solution.

The above considerations would indicate that anti-collision lights should have effective intensities of more than a 100 times that of regular position lights. But effective intensities of a flashing light are appreciably less than actual intensities, the effectiveness being a function of flash duration. This relationship was first expressed by Blondel and Rey (5) in the form:

$$I_e / I = t/(k + t) \tag{9}$$

Here I_e is the effective (equivalent fixed light) candle power of a flash of light of actual intensity I candles and of duration t seconds where k is an experimentally determined constant having a value of about 0.2 second. When the actual intensity varies appreciably during the flash as is the case of the sweep of a searchlight type beam across an observers eye, the above empirical expression may be refined into the form:

$$I_e = \frac{1}{0.2 + (t_2 - t_1)} \int_{t_1}^{t_2} I(t)\, dt \tag{10}$$

Some rotating anti-collision lights currently in use have a horizontal beam spread of about 10 degrees. Consequently if rotational speed is approximately 45 rpm, the $(t_2 - t_1)$ duration is about 0.04 second. Thus, based on an average candle power of about one half of peak, the resulting intensity would be approximately 1/12 of the peak beam candle power. This results in a factor of only about 10 rather over 100 for the relative effectiveness of the anti-collision light compared to the forward intensity of conventional position lights. This comparison of course should include flashing of the regular wing tip and tail units. But these flash durations range from about 0.4 to 0.8 second with close to full intensity throughout. Hence the effective intensity varies from about 0.7 to 0.8 of maximum candle power. This small decrease is of relatively little significance with respect to the comparisons just made. These values also show that doubling the flashing rate of conventional position lights from 40 to 80 cycles per minute to increase their overall conspicuity can be done with only a slight decrease in the effective intensity for each individual flash. This would be especially true for those systems which formerly used 0.5 for the on-to-off ratio if at the doubled rate the ratio were increased to about 0.7.

The effectiveness of the sweeping horizontal anit-collision light beam decreases for vertical angles above and below that corresponding to maximum horizontal spread and candle power. The decrease results from both the lower candle power and the narrower horizontal beam spread in the distribution at progressively higher and lower vertical angles. And suddenly both are zero except for the relatively weak direct filament light; the total vertical beam spread being about 10 degrees for some anti-collision lights or at least for the main beam of those having a second less intense beam but with increased vertical spread. This narrow vertical coverage is the major limitation of rotating beam anti-collision lights.

It is true that much of the time aircraft are operated on a level flight path. For such flying the rotating beam offers an appreciably better light signal to other aircraft at closely the same altitude. Especially for clear weather conditions, the increased punch and conspicuity afforded should compensate at least a little for the possible lethargic condition that extended nighttime cruising might induce in the officers and crew. But when this same aircraft is climbing or descending at angles exceeding the vertical beam divergence of the anti-collision light, no signal therefrom is available fore and aft to other aircraft at approximately the same instantaneous altitude. Similarly when banking for turns, there is no sideways signal in the true horizontal plane. Unfortunately, climbing, descending and turning are normal operations around airports where traffic is greatest. The limitation of a vertical beam spread of the order of 10 degrees accounts for the addition in some cases of a secondary beam having several times the vertical spread of the primary beam. However, for equal horizontal spread and total luminous flux, the signal effectiveness would be inversely proportional to the vertical beam spread. Moreover, in order to compensate for normal extremes of climb, descent and banking a total vertical spread of probably as much as 70 degrees is required. Such a spread would reduce the effective intensity of present anti-collision lights to at most only a few times that of conventional position lights.

Red has been chosen as the signal color for anti-collision lights because: (1) it is more readily recognized against an urban background, especially the contrast red affords with vehicle headlights passing under or beside trees, other vehicles, buildings, etc. which cause them to have a flashing appearance, (2) the light scattered from the beam during hazy or misty atmospheric conditions is less distracting to the pilot as it sweeps across his field of view than would be the case for any other color, and (3) a colored flash rules out confusion with an overtaking situation since a white light could be confused with the flashing white taillight.

The seventy-odd percent absorption of tungsten filament light by red filters is not so detrimental for this application as might be first assumed. Based on the inverse-square law of illumination only, one-quarter the intensity provides for one-half the range. But as soon as atmospheric absorption is considered also a range of 20 miles is only reduced to 16 to 18 miles by introducing a red filter and as the weather becomes worse the percentage decrease becomes less and less. Reason (2) above for the choice of red also partially explains the choice of vertical fin mounting for anti-collision lights. On large aircraft, the top of the fin is appreciably higher than the pilots eye level and consequently the essentially horizontal sweep of the beam is as high as possible above the pilot's forward field of view. Hence the backward scattering of light during less favorable atmospheric conditions is less objectionable. But of about equal importance for fin mounting is the greater expanse of unobstructed view from other aircraft that is thus provided. Fuselage mounting requires lights on both the top and bottom in order to equal the overall view afforded by the top of the fin installations.

Up to the present, more and more exterior lights have been added on aircraft to attain more conspicuity. Flashing and the rotation of beams has been introduced for the same purpose. But the sum total effect of wing and tail, fuselage, passing, landing and anti-collision lights blinking on and off and in and out of phase in red, green, white and sometimes yellow colors is not conducive to directional information. Repeated flight tests have shown that good directional information is obtained by limiting this aggregation of lights to only the forward and rear position ones and operating these steady without flashing. The tests further showed that any additional lights steady or flashing or the flashing of any or all of the position lights detracted from the directional information available from the steady position lights used solely.

This simplified signal presentation for directional information plus an anti-collision light for maximum conspicuity has considerable merit despite the limitations of the latter. If deemed necessary to compensate for the lack of vertical coverage of the anti-collision lights, consideration may be given to the flashing of the forward and rear position lights rather than operating them steady. Such flashing would also provide some conspicuity in the horizontal plane whenever the anti-collision lights become inoperative.

However if the position lights are flashed in conjunction with the use of an anti-collision light it is very desirable that the off period be a short as practicable and that the on period be at least several times that of the flash duration of the sweeping beam of the anti-collision li Otherwise, when the two signals are in phase the more effective anti-col signal would obliterate that from the position lights unless the range w so short that the two signals were fully resolved. Such obliteration wo destroy all directional information the position light sector colors cou provide. Even when using an on-to-off ratio of 2.5 and a flashing rate about 80 per minute, flight tests showed that some two to five red wing position light flashes were required before being sure that there were t types of flashes and that one was from the wing and one was from the ant collision light. Not until this decision had been made could one be cer that directional information was also available from the multi-red flas pattern. Equal directional information seemingly was determinable in ha the time or less when the position lights were changed to steady operat The advantage of steady over flashing for the green wing and white tail position lights was not so great as for the red wing light because the c contrast assisted in making the initial decision and the desired direct information consequently was forthcoming sooner.

XI. CONDENSER DISCHARGE FLASH TUBE SOURCES

The relatively recent innovation of progressively flashing the components of a row of condenser discharge airport approach lights for leading the pilot towards the end of the runway has since been partiall duplicated in principle for indicating the direction of flight of aircr The individual units of top and bottom rows of fuselage mounted condens discharge lamps are flashed successively from aft forward. The broadsi view at close ranges of the pattern thus formed by a row of three light is rather striking. The successive flashes in each sequence follow eac other at about 0.01 second intervals with complete sequences repeated e second or so.

On long fuselage aircraft, the individual lights of the system may spaced sufficiently far apart to provide the intended direction of moti information at ranges of a few miles or so when viewed perpendicular t the rows of lights. Air to ground observations of an experimental grou installation inferred that for an overall length of 40 feet for three l per row, direction information at a distance up to about 3 miles could obtained. However, when the line of sight makes an angle of less than 90 degrees with the rows of lights, the maximum distance at which direc information is obtainable would be presumably proportional to the cosin of the viewing angle. Thus for viewing angles of more than 75 degrees, i.e. less than 15 degrees with the flight axis, the maximum distance fo obtaining direction information would be less than one-fourth that obta from the side. Hence at the very angles of view where it is generally considered that direction of motion information is most desired these sequential flashes become ineffectual for this purpose at useful ranges

On the other hand, these condenser discharge sources fill at least a hemisphere with light. Consequently they are not subject to the major limitation of rotating beam anti-collision lights where the signal is missing from much of the horizontal plane during climbing, descending and banking and from much above and below the horizontal plane during level flight. But to date the maximum range near the horizontal of the condenser discharge sources has not been as great as that obtainable by the average rotating beam anti-collision light. This difference would undoubtedly be appreciably greater if the preferred red color was also imposed upon the condenser discharge systems.

Experience may show that the red color is very desirable if condenser discharge lamps are to be operated during dense haze or light fog conditions. A "white" condenser discharge lamp was being tested on a Bonanza aircraft when it passed through a thin overcast. The periodically illuminated cloud layer was so annoying that the pilot immediately turned off the lamp and protested when asked to turn it on again even for only a few flashes. The annoyance may be appreciably less on large aircraft when the closest lamp can be kept several times ten feet from the cockpit. However, one may find it advantageous to consider passenger comfort during these adverse atmospheric conditions in making an overall evaluation of the use of condensor discharge lamps.

XII. PILOTS AND AIRCRAFT VS SLOWLY CONVERGING COURSES

Conclusion No. 3 in a recent CAA report (6) states:

"3. This study has pointed out that a severe collision hazard exists where aircraft are flying in the same general direction and at approximately the same speeds. It must also be pointed out, however, that during this critical condition the closing rate is small and, if an auxiliary means of viewing this area were available, the pilots would have sufficient time to execute evasive maneuvers in time to avoid collision."

The reference to auxiliary means is made because of the insideous conditions here prevailing at the instant of collision; namely, the second aircraft must be above, below or on one side or the other of the first aircraft. And presumably, the two aircraft had been in these same or nearly so relative positions for some time. Except for fighter aircraft with bubble canopies, pilots cannot see upward or downward or much to the rear out of the cockpit. Moreover, few pilots will keep a sharp look-out for other aircraft directly to the side when cruising.

Prolonged cruising is monotonous and the use of autopilots makes it even more probable that a state of lethargic indifference will be attained by the very personnel which should be maintaining a competent watch. For night flying, extremely conspicuous lights would have to be employed to combat such conditions. And unless the bursts of light had such enormous intensities that scattered light would arouse the personnel concerned, they would be useless if the required signal is hidden from view by the opaque portions of the cockpit. Cockpit canopies on fighter aircraft permit viewing in directions exceeding somewhat a hemisphere. But most other fixed wing aircraft have a visual solid angle that is very much less. Exterior lighting practice cannot be expected to overcome deficiencies in the pilot's visual field of view. Only by the aid of auxiliary means will full coverage throughout a complete spherical field of view be attained.

XIII. TAILLIGHTS ON MILITARY AIRCRAFT

Because red was already required for the port forward position light, the military took exception when the CAA prescribed the alternately flashing red and white two-color taillight system. As a compromise, military aircraft were equipped with alternately flashing white and yellow taillights. At very short ranges a difference in these two signal colors can be seen. But at any practical distance such as the minimum one would desire to maintain between aircraft not flying formation, no significant difference in appearance of the alternate flashes is apparent.

Even at very short ranges where the yellow component can be seen as such it is believed that the conspicuity of the yellow-white system is obtained almost entirely from the flashing characteristic and very little results from the relatively small difference in color of the alternate flashes. Consequently it is further believed that replacement of the yellow flash by a second white flash would not cause any more loss in effectiveness at short ranges than would be compensated by a slight increased maximum range of the white over the yellow signal. The second white flash of course could be provided by the original white unit.

There may be merit in providing two lamps in a white taillight unit. If no other light but the tail unit is visible from overtaking aircraft, a two lamp unit would offer an appreciable increase in safety by maintaining a signal in the event of failure of one of the lamps. Approaches other than overtaking involve observations from both aircraft. Loss of a signal from one of the forward position lights does not prevent the observance of the light signals on the other aircraft.

The addition of an anti-collision light would further cancel any possible superiority yellow flashes may have had. The rotating beam would identify the aircraft as such when observed from the rear as well as from the forward and the sides. Inclusion of yellow with the standard white flashes probably adds more confusion than useful information.

The necessity for a taillight signal directly aft on jet aircraft is questionable. The solid angle coverage may be small within which one may see into the jet engine and observe the bright flame. But it could be given due consideration when side of fin or fuselage mounted taillights provide less than specified intensities directly aft.

XIV. NIGHT VS DAYTIME VISUAL RANGE

In extremely clear atmospheres, anti-collision lights have been detected at night at ranges greater than 35 miles. It is very unlikely that these same aircraft could be seen at anywhere near such a distance during the daytime except for the chance condition when the aircraft forms a good mirror for reflecting the sun's rays towards the observer. At high altitudes and in the absence of clouds, anti-collision lights should normally have visual ranges of at least 30 miles during the night between evening and morning twilight periods. Visual ranges of this magnitude would afford suffient warning time for collision avoidance by transsonic aircraft. Thus for these conditions, exterior lights of practical power consumption can provide useful information which seldom is available during daylight hours.

There are two major reasons for the superiority of a light signal at night over the visual detection of an aircraft by day. They are contrast and resolving power. By day the airplane is normally seen as a dark object against a brighter background. Since at distances of several miles the vertical depth of the aircraft subtends an angle less than that corresponding to the resolving power of the human eye, one is not seeing an object as such. Also at the higher altitudes under consideration the background of the sky and also that of the horizon is darker than when nearer the earth's surface. This results in less contrast for detecting the usually darken aircraft. Conversely, red lights at night have a reasonably good contrast with the starlit sky background, especially when the flashing characteristic is added. Also the visibility of point sources of light is independent of the eye's resolving power. Only the level of illumination produced is of importance in comparing point sources. Dark adaptation with consequent increased eye sensitivity could also favor the night situation when the light level within the cockpit is low.

During moderate to poor atmospheric transmissivities and under an overcast such that the daytime cloud and terrain backgrounds have a fairly low brightness anti-collision lights may often have a greater visual detection range than the aircraft on which they are mounted. Thus lights of this type should be used during the daytime, especially near airports when the conditions stated exist.

XV. NOTES ON OTHER EXTERIOR LIGHTS

1. <u>Smaller Formation Lights</u>

Formation light fixtures should be capable of providing complete attitude information with the briefest possiole glance, moreover, any change in attitude should be detectable immediately. Since aircraft surface illumination is impractical, the desirable three-dimensional presentation must be relinquished. The second preference would be two dimensional made up of lines. One line coinciding with the wing and a second with the fuselage would be the minimum that could provide roll, pitch and yaw information.

But again it is impractical to provide long line type light sources on aircraft. Nevertheless, lines can be approximated by several dots and thus several small light sources can be used. However, many of the present installations could be improved by increasing the number of lights employed for providing the line type information. More fixtures could provide longer lines in some cases as well as closer spacing within each line. Smaller fixtures would be helpful if additional formation lights were made a requirement.

It is believed that the present AN3030 circular formation light is (1) larger than necessary, (2) is too fragile and (3) emits light in many unnecessary directions. These various defects could be partially overcome by the employment of a small meniscus type lens in place of the present prismatic type. Consideration should also be given to the use of a lamp even smaller than the present AN3121-313. These two changes could result in smaller and less fragile units.

2. Taxi Lights

Presently prescribed taxi lights are inadequate. On shifting from landing to taxi lights, the pilot is temporarily plunged into semi-darkness because the forward beam intensities are suddenly reduced by a factor of more than 50 in many cases. Taxi lights certainly should provide at least as much light as do the most recently improved automobile head-lights. Thus forward intensities of the order of 100,000 candles with adequate beam spread to illuminate taxiway turnoffs should be provided. For incandescent filament sources, the corresponding luminous flux will require the disappation of some 400 or more watts.

3. Controllable Search and Landing Lights for Fixed Wing Aircraft

The controllable search and landing light being used extensively on helicopters may have desirable characteristics for fixed wing aircraft. In addition to the partial rotation about the usual extend and retract axis, full rotation about a perpendicular axis which extends and retracts with the unit is provided. They could be used for auxiliary taxi lights, expecially for finding and making turns onto taxi ways. During flight, if suitable mounting locations are available, they could illuminate leading edges of wings and engine nacelles for inflight examination at night. They may very well be a partial answer to the join up problem of night refueling operations.

4. Higher Beam Candle Power Landing Lights

Higher landing speeds require a greater forward range of landing lights. Sweptback and delta wing configurations place outboard landing lights further back behind the pilots positions. Such installations also require higher beam candle powers. In as much as little increase in the brightness of tungsten filament sources can be expected, further consideration should be given to other light sources in order to provide for these higher intensities. High pressure mercury arcs are one type of higher brightness sources which should be further developed if possible for this use.

XVI. NOTES ON OPTICAL PROPERTIES OF TRANSPARENT COVERS OR FAIRINGS

1. Surface Reflections

Semi-flush or flush exterior lighting fixtures usually require that much of the emergent light make quite large angles with the normal to the outer surface of the transparent cover or fairing. Moreover, when these optical elements have more or less parallel inner and outer surfaces, the corresponding angles of incidence on the inner surfaces are also large. Large incident and emergent angles result in low transmission of the covers or fairings because of adverse reflections at the air boundaries of both the inner and outer surfaces. This becomes especially important when the large emergent angles coincide with forward directions where maximum intensities are desired.

The fraction of incident light reflected and refracted at (transmitted through) air to optical media boundaries was first deduced by Fresnel. Column 2 of Table IV gives the percentage of light transmitted across such a boundary as a function of the angle of emergence where the index of refraction of the optical media is 1.5. These values multiplied by 0.95 would give approximately the overall tranmission for cover or fairing where the light entered at small angles of incidence and emerged at the angles listed in the first column.

The values in the third column are the square of the corresponding values in Column 2. These squared values apply to the combined effect of the two boundaries of a flat sheet of transparent material where the incident and emergent angles are equal; they are approximate values however, since no account is given to multiple interior reflections. Multiple reflections would increase somewhat the values for the larger angles but the listed valued are accurate enough for engineering usages. It may be noted that when the equal angles of incidence and emergence exceed about 77 degrees, the transparent sheet is a better reflector than a transmitter of light. Column 3 also applies without excessive error to glass or plastic curved sheets if the thicknesses are fairly uniform and the radii of curvature are not too small.

TABLE IV

LIGHT TRANSMISSION VS ANGLE OF EMERGENCE AND/OR INCIDENCE

FOR TRANSPARENT MATERIAL OF INDEX OF REFRACTION EQUAL TO 1.50

Angle of Emergence (degrees)	Transmission (percent)	
	Single Boundary	Combined Double Boundary
0	96.0	92.2
30	95.8	91.9
60	91.1	83.0
70	82.9	68.7
74	76.7	58.8
78	67.4	45.5
81	57.6	32.2
84	44.2	19.6
86	32.6	10.6
88	18.1	3.3

2. Prism or Lens Effect of Curved Surfaces

When light transmitting materials have curved surfaces, the direction of emergent light is not parallel to the incident direction if the angle of incidence is greater than zero. This "divergence effect" exists even though the inner and outer surfaces have a common center of curvature.

Figure 3 presents a set of self explanatory curves showing the deviation from parallelism of the incident and emergent ray for a light transmitting spherical shell. The curves cover a range for the ratio of inner radius to thickness from 0.5 to 512. This divergence at sharply curved surfaces accounts for the seemingly semi-opaqueness of some wing tip fairings and similar transparent enclosures on lighting fixtures. When much of the light is also reflected at the air to glass or plastic boundaries, the intensity without fairing or cover may be reduced to a very small fraction thereof when the enclosure is placed in position.

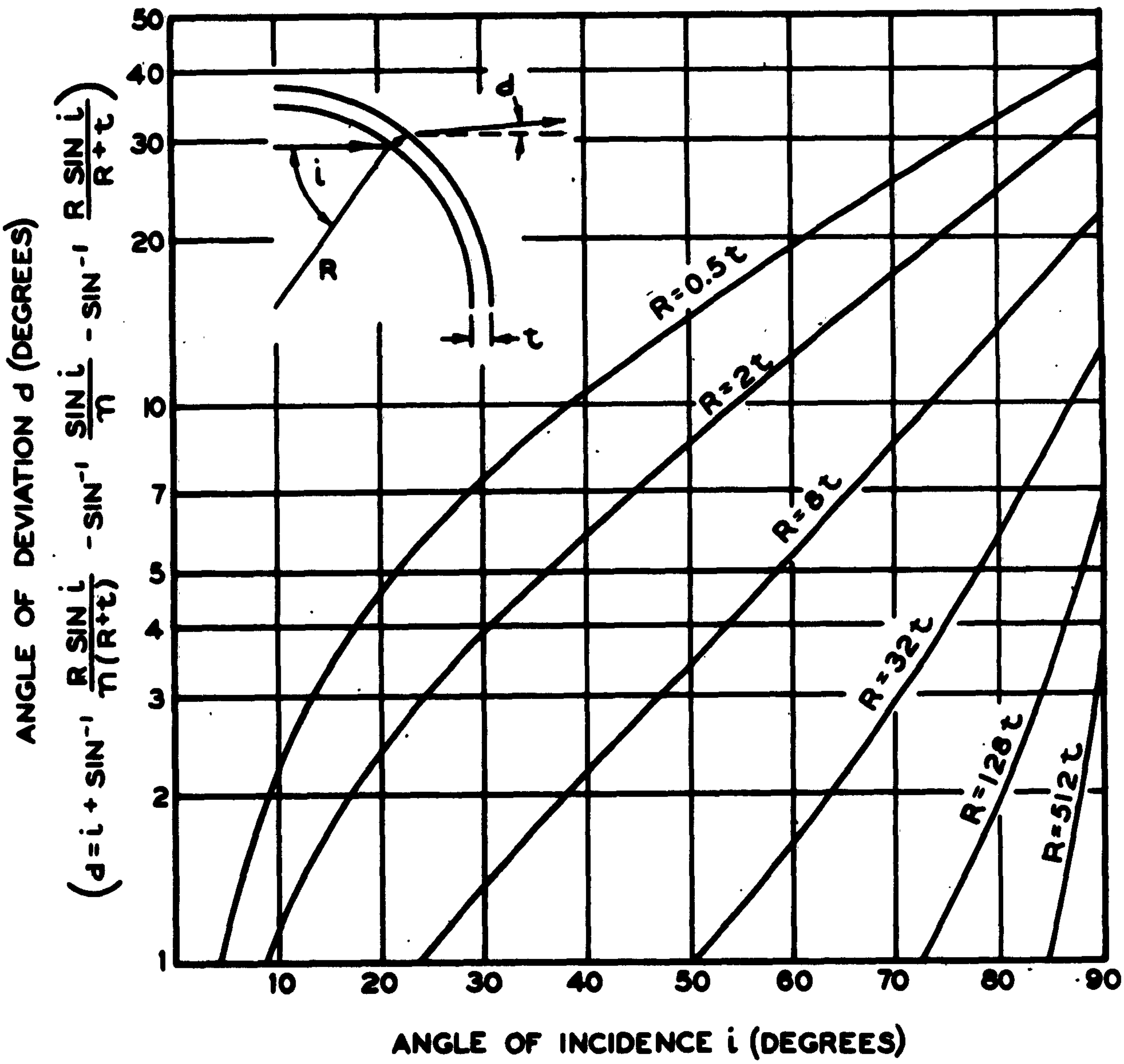

FIGURE 3. DEVIATION FROM PARALLELISM (d) OF LIGHT REFRACTED THROUGH SPHERICAL SHELL OF INNER RADIUS R, THICKNESS t AND INDEX OF REFRACTION, $n = 1.5$

XVII. SUMMARY AND CONCLUSIONS

Optimum candle power requirements for position lights have been determined subject to the choice of atmospheric transmissivity and practical power dissipation. A recommended forward position light minimum candle power distribution which should be obtainable by means of 40 watt tungsten filament lamps in hemispherical cover glasses is tabultated in Appendix A. The Appendix also lists the minimum intensities for the sector covered by the taillight. Repeated flight tests have shown that for exterior lights now in general use, best directional information is obtained when only non-flashing red and green forward and white tail position lights are employed. The flashing of these standard position lights and/or the addition of other exterior lights flashing or steady usually increases the overall conspicuity but adversely affects quick identification of direction.

Reduction of the outboard coverage of the red and green forward position light and a major increase in the dihedral angle required of the white taillight including intentional overlapping will increase the effectiveness of the directional information obtainable from the present red, green and white system without upsetting the past learning and experience of all pilots. Recommended coverage by these lights is presented in Appendix B.

Optimum position light flash rates and on-to-off flash characteristics as determined by flight tests are covered in the recommendations given in Appendix C.

Of all exterior lights flight tested individually and as parts of various systems, it is believed that the optimum navigation light system currently available would be non-flashing red and green forward and white tail lights plus one or two red rotating beam anti-collision lights. One anti-collision light is sufficient if top of vertical fin mounting on non-bubble canopy aircraft is feasible. Otherwise a bottom fuselage mounted unit in addition to one mounted somewhere on top is desirable. Because of the vertical limitations of rotating beam anti-collision lights and the desirability of non-flashing wing and tail lights, the above stated belief is premised on the use of two-lamp anti-collision light units for continuing conspicuity in case of one lamp failure. Moreover the filaments of these lamps should be visible at large vertical angles; at least up to and including 35 degrees above and below the horizontal in order that improved conspicuity is provided in at least this much of the preferred total spherical coverage. Because of the vertical limitation of presently available rotating anti-collision lights, effort should be made towards the development of units that will provide adequate vertical coverage.

Installation of forward position lights inboard from the wing tips even so far as on the sides of the fuselage, would not be detrimental to the providing of directional information. In fact, such inboard locations may be an improvement over wing tip mounting for extreme sweptback and delta wing aircraft. Inboard mounting however, may require the use of low intensity wing tip clearance lights.

Only for the very clearest atmosphere can practical anti-collision lights provide for adequate warning times for transsonic aircraft operating at level flight and approximately the same altitude. Consequently it is recommended that to the extent necessary the exterior lights installed on such aircraft be of the retractable type whenever flush fixtures are incapable of providing the desired spherical coverage with adequate intensity. Then all exterior light units could be flush for minimum aerodynamic drag during cruising and higher speed operations when lights are of doubtful value. Extension of the retracted units at slower speeds, especially in and near known traffic areas, might thus afford a reasonable measure of safety to itself and to the other aircraft in its immediate neighborhood. This recommendation is not intended to rule out the possible use of extended or fixed anti-collision lights on aircraft cruising at hight altitudes in extremely light traffic areas at night. The overall desirability of using lights at such times is difficult to evaluate. The upper atmosphere is so huge that the probability of two aircraft occupying the same space at the same time is very small. Hence the increase in safety such lights could provide may not be commensurate with the resultant aerodynamic drag and consequent extra fuel consumption and/or reduced speed of operation.

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APPENDIX

A. (1) Recommended Minimum Candle Power Distribution for Forward Position Lights (See Appendix B for Sector Coverage):

Angular Region (degrees) (3-dimensional angle b of Fig. 1	Candle Power** (minimum)
*. 0 to ± 10	60
±10 to ± 20	50
±20 to ± 30	32.5
±30 to ± 40	20
±40 to ± 80*	15

*In adjacent regions of overlap, the intensity shall be reduced in the first 15 degrees of overlap to less than 15 percent of the minimum intensity specified at the 15 degree extent of the overlap; the intensity shall be further reduced in the next 10 degrees to less than 2 candles and shall be maintained less than 2 candles elsewhere in the adjacent regions.

**In the forward port vertical dihedral angle, the color shall be aviation red and in the corresponding starboard sector the color shall be aviation green.

(2) Recommended Candle Power Distribution for Aviation White "Rear" Position Light (See Appendix B for Sector Coverage): A minimum of 15 candles shall be provided everywhere throughout a 255-degree vertical dihedral angle symmetrically placed with respect to the rear direction from the aircraft. In adjacent regions of overlap, the intensity shall be reduced in the first 15 degrees of overlap to less than 4 candles; the intensity shall be further deduced in the next 10 degrees to less than 2 candles and shall be maintained less than 2 candles elsewhere in adjacent regions.

B. Recommended Sector Coverage for Red, Green and White Position Light System:
Red--Forward and outboard 85 degrees to port side.
Green--Forward and outboard 85 degrees to starboard side.
White--Rear and outboard to both sides 135 degrees making a total vertical dihedral angle of 270 degrees.

Within each of these three sectors coverage includes from vertically downward to upward.

C. Recommended Position Light Flasher Characteristics Based on the Use of Tungsten Filament Lamps:

Flashing Rate: 75 to 95 cycles per minute (nominally 85 cpm)

On-to Off Ratio

Max. rated Lamp Current (amps)*	Ratio at Nominal Rate
1.5	between 3 and 4
3.0	between 2 and 2.7

*This maximum refers to the maximum for any signle lamp of the system and/or the maximum current for any single filament of multiple filament lamps.